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Imaging in Percutaneous Nephrolithotomy

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Abstract

Image guidance is a critical factor for the performance of urologic interventions. Percutaneous minimally invasive procedures have been developed and are being used with constantly increasing frequency. Procedures such as percutaneous nephrolithotomy (PCNL) are not performed without any image guidance.

Recent developments in medical imaging, such as three-dimensional radiographic fluoroscopy, CT, and magnetic resonance (MR) fluoroscopy, four-dimensional ultrasonography, and image fusion techniques, propose a new generation of image-guidance tools that promise to improve patient care. These developments have been used or have the potential to be used in PCNL and other urologic interventional procedures. Moreover, advanced needles and needle guidance systems provide a new perspective for the nephrolithotomy suite of the future.

The current review presents existing imaging technology in PCNL and interventional urology as well as advanced imaging techniques that are being or are expected to be evaluated in PCNL practice.

Introduction

Image guidance is a critical factor for the performance of urologic interventions. Percutaneous minimally invasive procedures have been developed and are being used with constantly increasing frequency. Procedures such as percutaneous nephrolithotomy (PCNL) are not performed without any image guidance. The puncture on the kidney, the following insertion of guidewires, establishment of the percutaneous tract, and the disintegration and removal of stones are based on the appropriate image guidance. The anatomic landmarks of the puncture site are insufficient for the performance of PCNL, and imageless techniques should never be applied because there is high risk of damage to vital structures through imprecise puncture.

Recent developments in medical imaging, such as three-dimensional (3-D) radiographic fluoroscopy, CT, magnetic resonance (MR) fluoroscopy, four-dimensional (4-D) ultrasonography (US), and image fusion techniques propose a new generation of image-guidance tools that promise to improve patient care. Moreover, advanced needles and intraoperative guidance systems provide a new perspective for the nephrolithotomy suite of the future. These developments have been used or have the potential to be used in PCNL and other urologic interventional procedures.

The current review presents existing imaging technology in PCNL and interventional urology as well as advanced imaging techniques that are being or are expected to be evaluated in PCNL practice.

Imaging Techniques of the Endourology Suite of Today

Radiographic fluoroscopy represents the most commonly used imaging modality for urologic interventional guidance. The real-time two-dimensional (2-D) images are helpful in the performance of various urologic procedures, such as renal biopsy, PCNL, and ureteroscopy. Specifically, the needle puncture in PCNL is usually performed under fluoroscopic (or less commonly US) guidance. The choice of the imaging modality is based on the preference of the surgeon.

Fluoroscopy is useful during the advancement of guidewires, tract dilatation, stone removal, and nephrostomy placement.[1] Fluoroscopic guidance provides real-time depiction of the collecting system and the included stones. The PCNL procedure is performed with a combination of fluoroscopic and endoscopic visualization of the collecting system. Because fluoroscopy is a 2-D method and provides limited information regarding the surrounding soft tissue, an injury to organs such as the colon could take place. Nevertheless, fluoroscopy has proven to be an invaluable tool for the performance of percutaneous procedures of the kidney and collecting system.

The introduction of digital radiography contributed to the reduction of radiation exposure as well as to the improvement of image quality. The combination of digital radiography with image storage systems and use of image processing systems resulted in the prevention of unnecessary image duplication and facilitated preoperative planning. Moreover,

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the projection of these images during the procedure in the operating room renders the technique a useful tool for the surgeon.[2]

The static imaging of the urinary tract as presented by plain abdominal radiography remains a useful tool for preoperative planning and postoperative detection of residual stones in PCNL. Despite the advantages of rapid and ready availability, the sensitivity of the method is low. Sensitivity and specificity rates range 58% to 62% and 67% to 69%, respectively.[3,4] Anatomic relationship of the kidney with the surrounding organs is not presented in this modality.

Intravenous urography (IVU) provides a detailed depiction of the collecting system and reveals the relationship of the collecting system to the ribs. The selection of supracostal access could be performed with the help of IVU. The puncture of stone-bearing caliceal diverticula is greatly facilitated by IVU.[4] IVU has been replaced by CT in some institutions, because the latter method provides superior detection capabilities for renal and ureteral stones.[5,6]

US has proven to be an advantageous imaging modality by providing effective, radiation-free, portable, safe, and quick imaging information. Moreover, US is not related to complications. Large intrarenal stones and hydronephrosis are easily detected by US. US, however, is related to limited identification ability of the collecting system anatomy as well as limited targeting ability in a non-distended collecting system. Small renal or ureteral stones are revealed with difficulty by US. Poor imaging quality in obese patients and in the ability to differentiate between nephrolithiasis and nephrocalcinosis are problems of the methods.

US has been used by several groups for the guidance of PCNL especially during the puncture of the collecting system.[7] The performance of PCNL puncture with US guidance without any use of fluoroscopy has also been reported.[8] US represents the modality of choice for a selected patient population, such as pregnant or transplant patients.[9–11]

Conventional CT has been used for diagnosis of urologic disease for many years. Recently, the unenhanced helical CT has been rendered a serious alternative to IVU.[12,13] The technique is superior to IVU in the evaluation of patients with renal colic and provides sensitivity and specificity for ureteral stones up to 100% and 97%, respectively.[4] For the preoperative planning, helical CT provides depiction of the extent, orientation, and location of renal calculi, which are useful for access selection in percutaneous procedures.[4,14,15] In addition, the anatomic relationships of the collecting system with surrounding organs are delineated, and the performance of a safe puncture is possible.[16,17] Nevertheless, the inability to provide real-time imaging capability has prevented wider application of CT in interventional procedures.[18]

CT after PCNL provides sensitivity and specificity of 100% and 62% in the detection of residual stones, respectively. The respective figures for plain abdominal radiography are 46% and 82%.[4] Although stone detection sensitivity of CT is excellent, the estimation of stone size is unreliable.[4]

The 3-D reconstruction of CT images for planning of percutaneous procedures has been reported to be feasible and accurate.[14] The collecting system and the renal parenchyma are accurately depicted with CT urography (contrast enhanced CT).[15,19] With the use of 3-D rendering software, anatomic relationships of the collecting system are provided, and access selection is facilitated (Figs. 1 and 2).

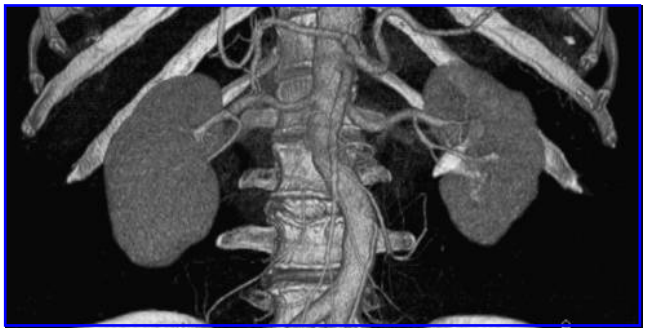

FIG. 1. Volume rendered three-dimensional image of a patient with a staghorn stone in the left kidney. Notice the anatomic relationships with surrounding structures.

The usefulness of 3D-reconstructed CT images, however, is not widely acceptable.[4] 3D CT rendered images that combine axial CT, CT urography, and angiography have been used for preoperative planning of urologic procedures such as nephron-sparing surgery. Renal lesions and vessels could be accurately detected.[20,21] A similar technique has been used for stone and ureteropelvic junction preoperative planning.[22] Recent improvements in CT technology provided rapid and continuous reconstruction of CT raw data and resulted in producing real-time CT imaging (CT fluoroscopy).[23]

MRI provides better depiction of the soft-tissue in comparison with fluoroscopy and CT but remains unreliable for the identification of stones in the collecting system or ureter.[4] MRI can be obtained without exposure to ionizing radiation. Thus, the technique may be considered as an alternative to US in selected cases such as for pregnant patients. Nevertheless, the strong magnetic field used interferes with ferromagnetic foreign bodies or electronic medical devices (eg, pacemakers and defibrillators) that are frequently carried by patients. Improvements in electronic medical devices have already minimized the aforementioned problem.[24]

Newly introduced multisensor/detector and faster image processing systems as well as new, more advanced MRI scanners have rendered real-time imaging a reality (MR fluoroscopy).[25] The latter technique has been used in interventional cardiology.[26] Percutaneous nephrostomy placement has been performed with the use of open configuration MRI.[9] MR urography represents an evolving imaging mo-

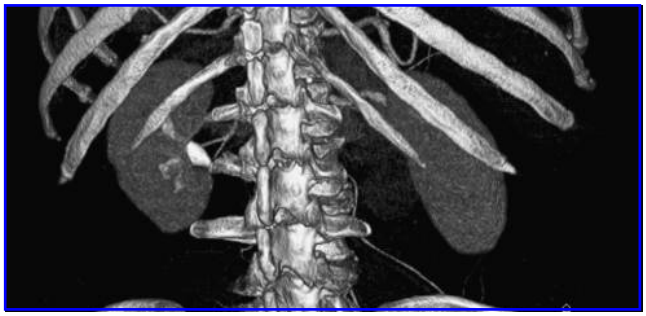

FIG. 2. Volume rendered three-dimensional (3-D) image of a patient with a staghorn stone in the left kidney. The 3-D image is rotated to better present the dorsal anatomic structures surrounding the kidney as well as the relation of the stone with the calices.

dality that allows optimal noninvasive evaluation of many abnormalities of the urinary tract. The application of several technical modifications provides adequate information for preoperative planning and postoperative assessment.[27]

Imaging in the Endourology Suite of the Future

New imaging techniques are being developed constantly. Despite the limited use of these techniques, experience and application range are expected to increase in the following years. The expansion of the use of novel imaging techniques may influence the performance of PCNL.

A relatively recently introduced technique is rotational fluoroscopy. During the performance of the method, the fluoroscopy C-arm makes a 180-degree rotational arc around the patient who is positioned on the operating table. The movement takes place in 5 to 20 seconds. High-quality reconstructed 3-D images are obtained. Localization of calcifications such as kidney stones in relation to the renal anatomy and depiction of the kidney in multiplanar contrast enhanced images is possible with rotational fluoroscopy.[28] Percutaneous and endoscopic urologic interventions may benefit from the improved image guidance of rotational fluoroscopy, because the technique could help in procedure planning and accurate performance of the intervention.

Technologic advancement of US hardware has rendered 3-D US imaging possible.[29] 3-D images are obtained from a single sweep of the US probe, which provides 360-degree viewing of the scanned area. The user-dependent problem of 2-D US interpretation is eliminated with 3-D US.[30] In addition, 3-D US provides improved accuracy in volume measurements. Reconstruction in different planes such as coronal, sagittal, or axial is possible. The comparison of consecutive examination for patient follow-up could be easier performed by the above technique. The need for highly trained technologists and the introduction of artifacts during image reconstruction are problems related to the method.[31]

3-D US was reported to be more accurate in comparison with 2-D US in the diagnostic evaluation of the bladder in patients with hematuria. The method has been used for the evaluation and follow-up of the urinary tract in pediatric patients with hydronephrosis.[32]

New ultrasound equipment provides real-time 3-D images, which are also referred to as 4-D US. The technique is based on projection of consecutive 3-D image sets with rapid refresh rates. Refresh rate ranges between 4 and 16 volume acquisitions/second and is related to probe and field size.[33] The projection of 4-D images is continuous, which results in avoidance of 3-D US time delays. The method could be used to study various renal lesions. Calcifications, complex cysts, and solid masses could be evaluated with the use of the provided volumetric data.

Transrectal 4-D US-guided prostate biopsies provide improved puncture and subsequent diagnostic accuracy.[34] A needle guided by conventional US is likely to miss the site of interest. 4-D technology provides accurate needle placement by allowing the needle tip to be localized in two or three perpendicular planes simultaneously.[35]

The virtual projection of the US puncture tract onto fluoroscopic images has been recently evaluated in experimental model and is under clinical evaluation.[36] Evaluation of 3-D and 4-D US for potential use in PCNL is ongoing with *in-vitro* experimentation in an attempt to elucidate the accuracy of the technique.[37,38] The 4-D US have proven to be at least as accurate as 2-D US in terms of quality of punctures, but improvement of US technology should be expected for the method to be established.[39]

An interesting field for further improvement of US imaging is US contrast agents, which have been used to improve depiction of renal and prostatic lesions with very limited clinical experience.[39–41] Current laboratory and clinical studies have revealed that US contrast agents are very efficacious in enhancing the US obtained images. The indications of contrast US are often similar to those of contrast CT.[31]

With introduction of CT fluoroscopy, real-time CT can be performed in the operating room. Guidance during PCNL is a possible application of the method. Accurate puncture, and residual stone and hydrothorax detection are possible advantages of the technique.[4] Nevertheless, CT fluoroscopy has not been evaluated in PCNL yet.

CT-guided percutaneous access for nephrostomy insertion has been reported.[42] CT fluoroscopy has been used for biopsies of lung nodules, which are particularly demanding. Real-time visualization of transthoracic needle placement using CT fluoroscopy has helped to overcome the difficulty caused by the movement of the lung fields during respiration and has improved biopsy performance.[18,43]

Biopsies, fluid aspiration, drainage, and catheter placement in the abdomen or pelvis have been performed with CT fluoroscopy guidance.[44] Percutaneous cryoablation of renal tumors was reported to be guided by real-time CT fluoroscopy.[45] Considering the above advancements, the technique is expected to be evaluated in PCNL.

The major disadvantage of CT fluoroscopy is the radiation exposure, especially for the physician. Intermittent imaging, use of needle holders, and selective scanning of the needle tip have been proposed to decrease radiation exposure.[46] Moreover, precise puncture is usually demanding to perform, and the combination of laser guidance systems with CT fluoroscopy represents a promising method to overcome the problem.[47]

Flat-panel volume CT is an innovative design that provides coverage of large volume per rotation, fluoroscopic dynamic imaging. Complex anatomic structures are depicted with high spatial accuracy.[48] Detector rows of the multidetector scanner have been replaced by an area of detectors. A similar new technique is the intraoperative angiographic CT (ACT), which uses cone beam reconstruction software and C-arm mounted flat panel detectors for the generation of CT resembling 3-D images from rotational angiographic acquisition. The technique has been used for the detection and correction of endovascular grafts as well as stents.[49,50] Embolization of cerebral aneurysms was also feasible.[51]

The important advantages of ACT are in the acquisition of the images while the patient is on the operating table during the intervention as well as resolution that is higher than fluoroscopy. Moreover, the accessibility of the system offers greater flexibility in setting the detector around the patient. The flat-panel based C-arm system provides better ease of use and worse accuracy in comparison to flat panel CT and lacks the temporally evolving 4-D processes of the latter system.[48] A similar technique using a rotational angiographic unit to provide CT-like images has been used for percutaneous vertebroplasty with promising results. Requirement of multi-modality

imaging for the planning and performance of the procedure was avoided with the use of the technique.[52]

In urology, DynaCT (Siemens, Germany) is a novel imaging modality that combines high resolution flat-panel fluoroscopy with CT capability and 3-D reconstruction in the endourology suite. Preoperative planning, real-time intraoperative data, and postoperative evaluation could be performed with the use of DynaCT. PCNL procedures have been performed with high accuracy.[53]

Recently introduced MRI technologies represent the future of MR imaging techniques. Dynamic contrast-enhanced MRI and MR spectroscopy have rendered MRI as an important tool for staging and treatment planning in patients with various diseases, such as prostate cancer. Although material and biomedical engineering improvements have led to simultaneous advances in instrumentation and robotics that can be used with MRI,[54,55] instrumentation represents a problem for interventional MRI (iMRI), because the ferromagnetic material may result in artifact production in MRI images. In addition, these instruments are subjects to torque and displacement in the magnetic field and may become a projectile.[56]

The use of a C-arm shaped MRI system has been used for the performance of percutaneous nephrostomy with success.[57] High-resolution images with precise anatomic detail can be provided by iMRI without the disadvantage of radiation exposure. The latter problem has particular importance in children and pregnant women, while the personnel of the interventional suite avoid the everyday radiation exposure. Multiplanar capabilities facilitate the puncture of difficult targets. MRI is not influenced by air-filled structures, such as bowel or pleural space, and has an additional advantage in the imaging of liquid-filled structures (urinary tract). The open (C-arm shaped) design of the system provides excellent accessibility to the patient.[57]

The efficacy of a closed bore MR system for tracking and guidance of needle interventions has been assessed in experimental models. Active marker coils were used for tracking the needle, and the repositioning of the imaging system was automatically performed. Moreover, a robot was used for needle position and puncture performance. The robot provides high mechanical stability and precision.[58]

Combination of the data obtained by the aforementioned imaging techniques has been proposed in an attempt to gain additional information. Image fusion technologies and image-augmented navigation have been introduced and represent an intriguing option for medical applications. These techniques enable full image projection in the operating room of the future. Images obtained previously by CT scans and MRIs can be formatted into 3-D image sets.

An interesting option for planning of percutaneous procedures is the combination of CT urography with conventional radiographs or IVU, resulting in hybrid images. The efficacy of these methods is not yet proven.[12,59] Combination of these image sets with images obtained by other modalities to make a single image including all the information would help the surgical approach with respect to anatomic boundaries as well as precise surgical excision. These techniques facilitate complication prevention and improve the outcome of the procedure.

A further development of image fusion techniques is the frameless stereotactic navigation that allows interactive visualization of instrument position in conjunction with preoperatively obtained CT images.

Specifically, navigation systems have been divided in different groups according to their distinctive system attributes. Among the navigation systems characteristics shared are intraoperative imaging, tracking devices, organ shift, and tissue deformation as well as user interface.[60] Intraoperative imaging includes image acquisition and registration. The intraoperative image acquisition attempts to overcome organ shift and tissue deformation. Intraoperative US (2-D and 3-D), open MRI guidance, and flat panel C-arm systems have been used for intraoperative imaging. Image registration provides the preoperative surgical plan before the initiation of the procedure. All data obtained from imaging modalities are processed and applied to the individual intraoperative anatomic characteristics of the patient.

Tracking devices are responsible for the link of spatial information from various devices. These devices provide a coordinated system composed of imaging modalities, surgical instruments, and endoscopes. Optical and electromagnetic tracking devices are available.[60] For example, interactive-image guidance, frameless stereotaxy, and intraoperative navigation with the use of preoperative images are possible in the interventional MRI suite. Optical tracking devices integrated within the MR scanner provide surgical intraoperative navigation in combination with nearly real-time imaging. Registration process between the patient and the obtained images is not necessary, because the acquisition of images was performed in the surgical position of the patient.[58,61] Thus, coordinates provided by the optical tracker can be used to control the scan plane of the nearly real-time imaging and to display a virtual instrument (eg, biopsy needle or therapy probe) and its trajectory, overlaid on the MR image.[62–64]

The organ shift and tissue deformation represent a problem for navigation, because the continuous movement of the tissue should be taken into consideration for accurate navigation. Mathematical models simulating the organ movement and tissue deformation have been used. Intraoperative organ surface displacement measurements are necessary to compensate for deformation.

Different navigation systems propose different user interfaces such as intraoperative 3-D visualization of structural information obtained by imaging modalities (CT). Virtual and augmented reality provides a real-time computer-generated virtual environment based on data obtained by imaging methods and has been used for intraoperative navigation.[60]

The use of 3-D-CT and 3-D-MRI data processed by appropriate surface and volume rendering software provides images that depict and simulate an endoscopic view of a hollow organ. The technique is also known as virtual endoscopy (VE). Images of the urinary system are obtained by opacification with contrast or insufflation with air/CO_2 of the urinary tract. VE enables visualization of difficult to access regions (strictures) and prevention of complications related to diagnostic or interventional procedures. Virtual cystoscopy and ureterorenoscopy have been performed with high sensitivity and specificity.[22,65,66]

Interesting developments for percutaneous interventions are the new types of needles and needle guidance systems. Needles that have the capability of active steering have been proposed. One of these needles uses a piezoelectric system to adjust needle tip position and can be steered to different di-

rection by selectively setting the input electric field.[67] Another flexible needle has been designed as a linear beam supported by virtual springs where the stiffness coefficients of the springs vary along the needle. The trajectory of the needle is calculated by a computer and the flexibility of the needle is used to overcome any obstacles in its path.[68]

Another development of needle technology is the bioimpedance measuring needle. The insertion of the needle in the collecting system results in the decrease of impedance. The initial evaluation showed that the needle confirmed accurately its insertion in the collecting system.[69]

Magnetic field navigation of the puncture needle has been introduced in an attempt to increase accuracy and to avoid complications. These systems have successfully performed percutaneous access for nephrostomy or intrahepatic portosystemic shunt in porcine models.[70,71] Computer-assisted renal puncture has been experimentally evaluated and observed to be accurate and less time consuming.[72]

Localizing active coils on puncture needles has been reported to facilitate the MRI-guided puncture by determining needle orientation and trajectory.[73,74,75] Robot-assisted needle guidance successfully performed percutaneous punctures with high accuracy and probably represents a future perspective for PCNL. Robotic percutaneous access with the PAKY system achieved safe and efficient access for PCNL.[76] Use of the same system proved to be more accurate but slower than the participating endourologists in a comparative study.[77] Recently, a US-guided robot-assisted needle placement has been reported to achieve more accurate puncture than manual insertion and reduced invasiveness.[78]

A Glimpse into the Endourology Suite of the Future

The rapidly developing and constantly accelerating research on imaging technology and interventional methodology makes the prediction of the endourology suite of the future a difficult task. Different imaging modalities would be integrated. A flat panel C-arm with 3-D/4-D US would have been an interesting option. Interventional MRI would also represent an alternative. Monitors in the suite would be projecting images from all modalities, and all data would be combined in a single fused image according to the preference of the endourologist. Puncture guidance would take place with the use of a robotic arm. The control of the robot would be performed from outside the suite so that the surgeon avoids radiation exposure.

Flexible needles capable of selective steering would be used. The trajectory of the needle and the correct insertion would be confirmed by magnetic guidance and bioimpedance measuring systems, respectively. After the insertion, advanced navigation systems would facilitate the performance of PCNL.

Conclusion

Medical imaging technology is under constant development with the introduction of novel techniques and the combination of existing imaging methods. PCNL and other interventional procedures continue to evolve and to adopt imaging developments as well as image-based guidance systems in an attempt to achieve higher standards of effectiveness and to improve intervention-related morbidity. Several newly introduced techniques are expected to be evaluated in the following years. It remains a question as to how these modalities would transform current PCNL practice.

Disclosure Statement

No competing financial interests exist.

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Abbreviations Used

ACT = angiographic computed tomography
CT = computed tomography
4-D = four-dimensional
iMRI = interventional magnetic resonance imaging
IVU = intravenous urography
MR = magnetic resonance
MRI = magnetic resonance imaging
PCNL = percutaneous nephrolithotomy
3-D = three-dimensional
2-D = two dimensional
US = ultrasonography
VE = virtual endoscopy

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